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A rapid tree diversity assessment method for cocoa agroforestry systems

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ABSTRACT

Biodiversity is recognized as an essential part of sustainable development efforts, however reducing biodiversity loss is a key global challenge that requires updated data on biodiversity status at different scales. Cocoa agroforests include tree species besides cocoa, a practice beneficial to biodiversity, ecosystem conservation and farming households. We present a stepwise procedure to test and select a method that rapidly assesses biodiversity in cocoa agroforests based primarily on species richness and counts of non-cocoa trees. Three rapid assessment methodologies (RapidBAM) with different sampling procedures were tested in three phases: calibration, testing and evaluation. Results showed the method using the lowest number of sample plots with a minimum area coverage and a consistent sampling time (regardless of farm context) provided the most accurate and straightforward assessment. Farmers accurately reported qualitatively on species, complimenting quantitative data produced by RapidBAM. Collecting biodiversity data with RapidBAM proved valuable to collect data at large-scales and is applicable to different landscapes. Monitoring biodiversity with fewer required resources than conventional methods is a relevant outcome, which can help defining efficient biodiversity-friendly farming practices.

1. Introduction

Biodiversity is recognized as an essential part of sustainable development efforts, particularly through its role on food security (Frison et al., 2011; Glamann et al., 2017; Sunderland, 2011), ecosystem conservation (Barrios et al., 2018; Mortimer et al., 2018; Rice and Greenberg, 2000) and climate change adaptation and mitigation (Hisano et al., 2018). Reducing biodiversity loss, which is increasing at an alarming rate, is a key challenge and a global effort (CBD, 2020; Rockström et al., 2009; Scherer et al., 2020) that requires updated data on biodiversity status at different scales.

Traditional agroforestry systems include tree species other than the main product, which can provide shade and complement household income and diet. This practice can bring benefits for biodiversity and ecosystem conservation and can foster the long-term sustainability of the production system (Daghela Bisseleua et al., 2013; Cerda et al., 2014; Sonwa et al., 2019; Tscharntke et al., 2011). In cocoa agroforests, non-cocoa trees are part of a shade management strategy that influences productivity levels and supports the maintenance of cocoa farms (Anglaaere et al., 2011; Asare et al., 2019; Asare et al., 2014; Bos and Sporn, 2012; Somarriba et al., 2014). Decreasing yields of cacao productivity, particularly in West Africa, have been attributed to poor management of disease and pest, to ageing cocoa trees and changes in shade strategies (Schroth et al., 2016; Wessel and Quist-Wessel, 2015). Recent trends also indicate a decrease in natural forests as they are cleared to establish new cocoa farms (Brobbey et al., 2020; Jalloh et al., 2012; Koua et al., 2020) and the replacement of native forest species by exotic tree crops with a higher market value (Sonwa et al., 2007; Sonwa et al., 2014). These circumstances can have either positive or negative effects with regards to biodiversity; on the one hand the introduction of new exotic species could increase overall numbers of species richness; on the other hand the removal of forest tree species increases the fragmentation of forest patches, affecting the integrity of ecosystems (Asare et al., 2014; Asare and Ræbild, 2016).

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Due to the growing concern with food quality and safety, the traceability of agricultural commodities and the implementation of sustainability standards have become more important (Tayleur et al., 2017). Globally, the private sector is increasingly interested in investing in product traceability and labelling, desirable in terms of tracking business productivity and efficiencies, but also for marketing and sales (Addison et al., 2020). Consumers are increasingly demanding for transparency in their food products, and are often prepared to pay for premium certified products that carry positive environmental and livelihood associations, such as fairtrade and rainforest alliance (Grabs and Carodenuto, 2021; Lambin and Thorlakson, 2018). These circumstances have fostered the implementation of several initiatives regarding traceability and sustainability standards also in the cocoa sector (Kroeger et al., 2017; Perez et al., 2020; Saltini et al., 2013), which are expected to be continuously expanding (Kroeger et al., 2017; Perez et al., 2020; Saltini et al., 2013). The assessment of biodiversity conditions is of primary importance, to manage cocoa agroforests, implementing suitable strategies to maintain productivity, farmers' income and the ecosystems' balance, and to monitor progress towards required biodiversity improvements on a global scale. In response, there is a need to identify alternative methods that can be easily and cost-effectively applied at large scales, Rapid biodiversity assessments are a possible approach, by implementing sampling protocols that allow rapid measurements of specific species and a straightforward identification of threats and priority areas for conservation. In addition, the implementation of such methods fosters community involvement and participation and assists decision-making processes in conservation management and policies (Patrick et al., 2014). Plant assessments approaches, can include categorizing plant functional types, counting and measuring specific key species, or counting trees and other vascular plants by size (Gillison, 2002; Kuncoro et al., 2006; McCullough et al., 2007; Oke and Odebiyi, 2007; Stohlgren et al., 1997; Vanclay et al., 1997). Despite these valuable efforts, constraints in available resources and the lack of consensus on indicators and methods, can hinder the implementation of such rapid assessment methodologies (Tanalgo et al., 2019).

Other possibilities for biodiversity monitoring rely on recent technological advances, such as the use of in-situ cameras, environmental DNA barcoding and remote sensing techniques (Alberton et al., 2017; Bruni et al., 2012; Papadopoulou et al., 2015; Peng et al., 2018; Wang and Gamon, 2019). However, their use can be limited by expert knowledge requirements, technical difficulties in image interpretation or the high costs of suitable high-resolution remote sensing products (Mulatu et al., 2017; Petrou et al., 2015; Stephenson, 2020). Other initiatives have recently emerged based on a citizen-science approach, which promotes the voluntary engagement of local people in activities that support scientific procedures, such as collecting in-situ data and carrying out surveys, even without particular expertise (Kelling et al., 2019; Pocock et al., 2018; Theobald et al., 2015). Such initiatives have also been tested in agricultural systems (Isaac and Martin, 2019; van de Gevel et al., 2020) and have a strong potential to foster the implementation of biodiversity monitoring activities at large scale.

In this context, our research had the main purpose to identify an alternative methodology for biodiversity assessment in agroforests, applied originally to cocoa fields and adaptable to other commodities produced in agroforestry systems. Based on parameters quickly collected from non-cocoa trees, we defined and tested different sampling procedures that could be easily integrated into existing traceability systems and information platforms. The data collected with such methodologies should provide helpful information to farmers, in order to improve their farming practices with biodiversity-friendly actions, towards achieving certification, increasing their income and supporting sustainable cocoa farming. This paper presents the procedure applied for defining, evaluating and selecting a rapid biodiversity assessment method, based on local field surveys, and discusses its potential to provide swift and up-to-date results and monitor biodiversity status in agroforests on a large-scale.

2. Materials and methods

2.1. Study areas

The study areas for the development of the methodology were a set of cocoa fields located in Ghana, West Africa, totalling 573 sample areas. Ghana is the second largest exporter of cocoa beans worldwide (Wessel and Quist-Wessel, 2015; Yamoah et al., 2020), and cocoa production occupies about 10% of the agricultural land, being the country's main export crop, accounting for 8.2% of the country's GDP and 30% of total export earnings (data from 2010). Western and Ashanti regions are the major producers, with 55% and 16% of the total production, respectively (COCOBOD, 2014), and national production has doubled between 2000 and 2010 (Asante-Poku and Angelucci, 2013). The large majority of cocoa (ca. 90%) is grown on smallholder farms (Wessel and Quist-Wessel, 2015), with over 25% of the country's population depending on the cocoa sector (Anthonio and Aikins, 2009). In most cocoa-producing households, cocoa accounts for over two thirds of household income (Kolavalli and Vigneri, 2011).

The field work was carried out in regions of southern and central Ghana, divided in several field work phases (Fig. 1). The selection of the cocoa fields depended on the farmers availability, since their participation, mostly on a voluntary basis, was required, and on the coverage of the traceability and mapping system (TMS) where this research was integrated (see section 2.2.). Despite some variations in the biogeographical conditions among these regions, they are all cacao growing areas and the main land cover types are mosaic of forest/cropland and closed evergreen lowland forest (Mayaux et al., 2004). In congruence with the objectives of this research in relation to the potential large-scale application and replicability of the methods, they were tested in different regions where cocoa is grown.

2.2. Traceability and mapping system

Traceability platforms currently available are developed within geographic information systems (GIS) and allow the mapping and cross-analysis of data regarding the origin of the product and farming practices, among other information. Our research was developed with the aim of offering tools also to support the traceability of cocoa production, specifically for biodiversity conditions, an objective that fits with the recently published standards for Sustainable & Traceable Cocoa[a] (ISO 34101: 2019). For this purpose, the rapid biodiversity assessment methodology, hereafter called RapidBAM, was tested as an additional component of an existing platform named Traceability and Mapping System (TMS)[b], which operates at large scale and collects data from several regions of the world, including West Africa. As such, the development of the biodiversity module could take advantage of the functions already put in place in TMS, but it can also be implemented as a stand-alone tool or be incorporated in other platforms. The integration of the biodiversity component in TMS followed specific requirements: i) the selected method would take approximately 30 min on each farm, additional to the current TMS data collection and mapping procedure; ii) the tools and sampling procedures had to be simple to apply, to enable the wider participation of local and non-expert people and to ensure scaling out for different contexts on a large-scale, even when resources are scarce; iii) to implement this new component of biodiversity, only the geolocation and mapping of cocoa fields with GPS technology are

[a] Online platform available at https://www.iso.org/obp/ui/#iso:std:iso:34101:-1:ed-1:v1:en

[b] Geotraceability, 2017, http://geotraceability.com. The platform has been changed recently and the traceability process is now called Intelligent Supply Chain

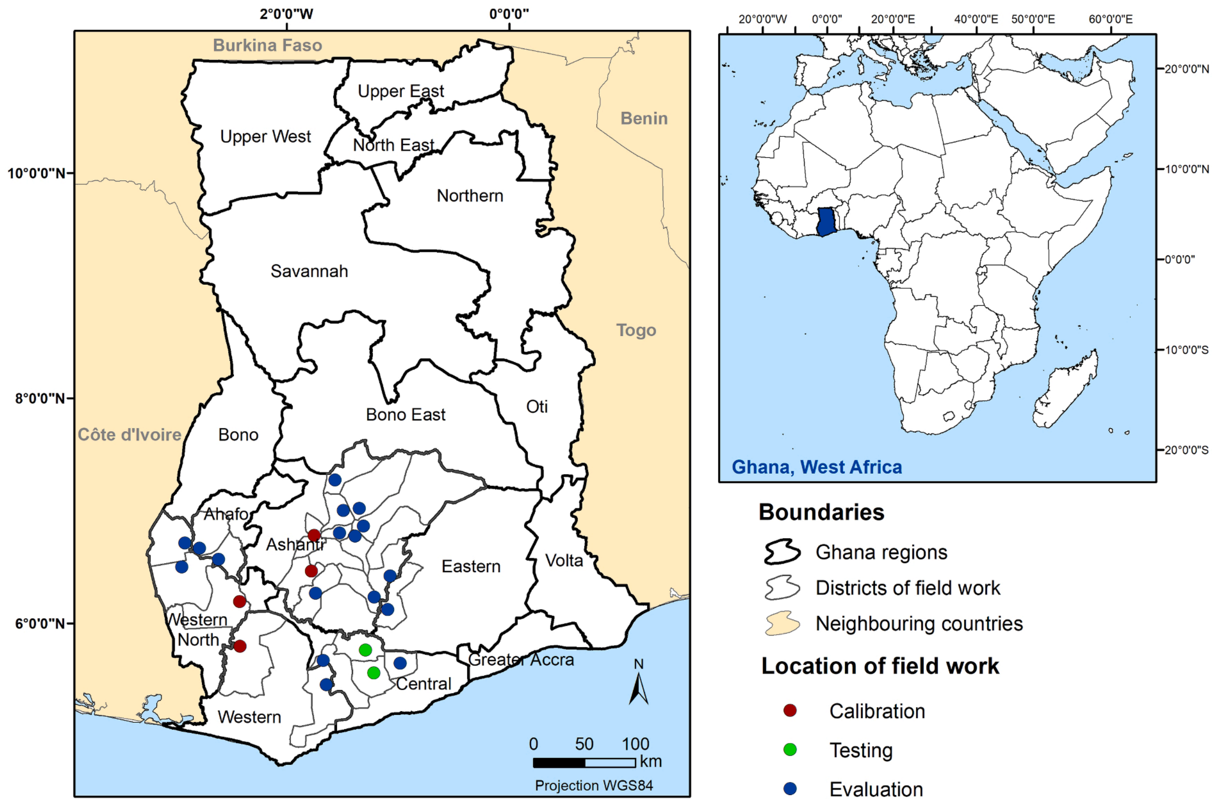

Fig. 1. Location of the regions and districts in Ghana where field work was carried out, in different phases, updated according to the new administrative divisions of 2019 (www.statsghana.gov.gh).

required beforehand, to capture field boundaries, size and shape.

2.3. Stepwise procedure for methods evaluation and selection

The selection of a suitable RapidBAM for large-scale application required the participation of multiple stakeholders, among which relevant government institutes, private industry and non-governmental organizations, with 1 to 3 members of each institution participating in the consultation process (Table 1). Their diversified knowledge, experience and complementary views provided a comprehensive evaluation of the methods' performance and suitability along the several stages of the selection process. This consultation process was carried out along 14 months, between August 2012 and October 2013, as part of the procedure to select a RapidBAM suitable for cocoa farms.

Table 1
Stakeholders engaged in the consultative selection process.

Institution	Type	Nr. participants
Armajaro Trading (currently Ecomtrading)	Industry	2
Traceability and Mapping System (TMS)	Industry	2–3
Ghana Cocoa Board	National Authority	1
Cocoa Research Institute of Ghana (CRIG)	Research Institute	1
Forestry Research Institute of Ghana	Research Institute	2
International Institute for Tropical Agriculture (IITA)	Research Institute	1
Bioversity International (IPGRI)	Research Institute	2–3
Conservation Alliance	Non-governmental (NGO)	1–2
Rainforest Alliance	Non-governmental (NGO)	1–2
UTZ Certified	Non-governmental (NGO)	1

*The number of effective participants varied by meeting during the consultative process.

The selection of a RapidBAM was carried out with a stepwise approach, by implementing several sequential steps to evaluate the methods and enable adjustments to improve the sampling procedures. This way, refinements to the data collection and analysis procedure could be introduced at each new phase, according to the outcomes of the stakeholders' consultative process and the results obtained in preceding steps. In total, there were four stakeholders' meetings during that year, based on group consultations and joint discussions, one in the early stage of the project and then in each phase of the stepwise approach to test and evaluate the methods proposed (Fig. 2).

2.3.1. Identification of biodiversity indicators

The identification of biodiversity indicators for cocoa agroforests was the first step. Based on stakeholder consultation and previous research (Anglaaere et al., 2011; Asare et al., 2009; Asare, 2005; Asare, 2006; Bayala et al., 2011; Deheuvels et al., 2012; Gillison, 2005; Jacobi et al., 2013; McCullough et al., 2007; Melo et al., 2003; Oke and Olatiilu, 2011; Rice and Greenberg, 2000; Ruf, 2011; Schroth and Harvey, 2007; Sidiyasa and Samsoedin, 2003; Sonwa, 2004; Sonwa et al., 2007; Sonwa et al., 2008; Wade et al., 2010), several parameters were selected and, accordingly, the data to collect in the field were defined. The focus of the study was on measurements from existing non-cocoa trees in cocoa fields. These are rather easy to capture, their presence or absence is mostly controlled by farmer choice, and they are a direct outcome of management strategies in agroforestry systems, which can be improved with biodiversity-friendly practices. Therefore, the number of trees and the number of tree species other than cocoa were the primary biodiversity indicators (Table 2). In addition, the measurement of diameter at breast height (dbh) of non-cocoa trees, the existence of dead trees standing and the adjacent land use to the cocoa field were also identified as relevant parameters. These were included during data collection,

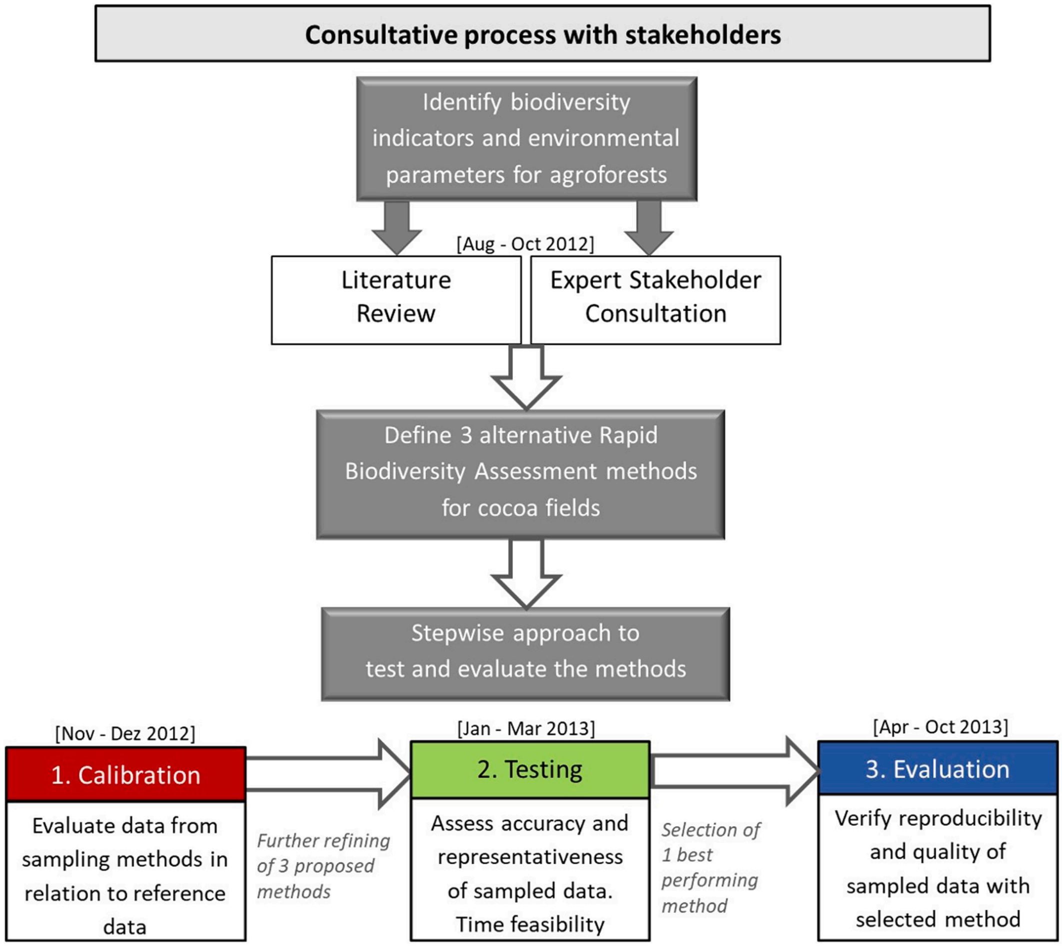

Fig. 2. Stepwise procedure applied to evaluate and select a method for rapid assessment of biodiversity in cocoa fields, in different periods along 14 months.

however they were not used as criteria to select a RapidBAM due to the inexistence of reference data required to evaluate the performance of the methods.

Information on tree abundance was deemed important, yet the consultative group recognized it was rather time-consuming and it could hinder the use of the method at large-scale. As such, this information was not directly included in the RapidBAM sampling procedure. As an alternative, the data were obtained with the assistance of the farmers, through a local participatory citizen-science style approach (van de Gevel et al., 2020), an option evaluated within the proposed procedure. The most common species found in Ghanaian cocoa farms were collated beforehand (Asare and Asare, 2008; Manu and Tetteh, 1987), including timber, food and other native and exotic trees. A pre-designed form was given to farmers to compile, asking them to provide information on the number of trees per each species they have on their respective farms.

2.3.2. *Definition of RapidBAM*

A literature review was carried out, specifically on existing alternatives to apply a rapid field assessment of biodiversity (Greco et al., 2012). After a preliminary selection, eight different methods were explored in detail, among which those based on the survey of plant functional types (Gillison, 2002; Gillison, 1996; Gillison et al., 2004; Vanclay et al., 1997), on significant or unique species (Mccullough et al., 2008; McCullough et al., 2007), on a plant assemblage analysis (Kuncoro et al., 2006) or that were specifically applied in agroforests (Oke and Odebiyi, 2007; Sonwa et al., 2009). The strengths and weaknesses of each method and their compatibility with the traceability and mapping system were analysed and discussed with the stakeholders (Greco et al., 2012). Despite differences in the information collected, the resources available and the conditions in the field, all the studies included sampling procedures based on transects or quadrat plots, which were used as guidelines for the design of the methods.

Three different RapidBAM methods were proposed and tested in the field, resulting from a necessary compromise between the diversity of possible methods, the objectives of our study, the compatibility with the traceability and mapping system and the resources available. In congruence with the discussed criteria, all three methods collected the same biodiversity parameters and included a similar inventory technique based on pre-defined forms, although these were adapted to each method. Conversely, each RapidBAM used a different plot definition and sampling procedure, where the area surveyed and the type of sample plot varied with the method (Fig. 3). As such, we tested the two dominant plot types, transect and quadrat, plus an additional alternative of a transect along the border of the cocoa fields, considering the possibility to join this activity with the mapping procedure of the cocoa fields that was already being done for the traceability and mapping platform (TMS). Capitalizing on this mapping procedure, which included the registry of GPS waypoints around the border of the cocoa field, at every 10 m or whenever there was a change in direction, the sampling procedures were designed taking into account the use of the waypoints as a primary location of the sample plots. Considering the average farm size of cocoa fields surveyed by TMS in Ghana (approximately 1.4 ha), and a corresponding farm perimeter of around 400–500 m, all three methods were designed to survey an area of at least 800 m^2 (5%), to allow extrapolation of the sample data without compromising the rapid assessment approach.

Method 1 – Transect along the border of the cocoa field

This methodology used the borderline of the farm as the transect; the

Table 2
Summary of the primary biodiversity indicators (number of non-cocoa trees and number of tree species): background of their relevance, data collection and analysis within the stepwise procedure developed.

Indicator	Number of non-cocoa trees
Background	The agroforestry system resulting from the maintenance of forest trees on-farm and/or the introduction of other native or exotic trees plays a major role in biodiversity conservation, and has the potential to increase on-farm cocoa yields and contribute to household income (Asare and David, 2010; Cerda et al., 2014; Clough et al., 2011; Clough et al., 2009; Tscharntke et al., 2011). In Ghana, the practice of keeping trees in cocoa farms has promoted the maintenance of indigenous tree species, such as Odum or African Teak (*Milicia excelsa* (Welw.) C.C.Berg), Otie, or African Nutmeg (*Pycnanthus angolensis* (Welw.) Warb.), Bako (*Tieghemella heckelii* (A. Chev.) Pierre ex Dubard), Asanfina (*Pouteria altissima* (A.Chev.) Baehni), Emere (*Terminalia ivorensis* A.Chev.), Ofram (*Terminalia superba* Engl. & Diels) or Mahogany (*Khaya ivorensis* A.Chev.) (Asare and Prah, 2011). Fruit trees such as avocado and mango are also common and provide shade for younger cocoa trees, food and an additional source of income for the household (Asare and Prah, 2011; Ruf, 2011).
Data collected	Non-cocoa trees of at least 10 cm diameter at breast height (dbh) or 31 cm girth, were counted. No differentiation per species. Oil palm trees and fruit trees included.
Analysis	Extrapolated to ha (number of trees on plots/plot area as calculated from GPS waypoints taken along farm boarder), variable per RapidBAM.
Indicator	**Number of tree species**
Background	Richness, the number of different tree species found on a farm, provides indication on the biological diversity of an area (Gotelli and Colwell, 2010; Schroth and Harvey, 2007; Wacker et al., 2009). Non-cocoa trees can support a variety of different ecosystem services that promote diversity (Asigbaase et al., 2019), including supporting pollination services and attracting insects to enrich the ecosystem (Adjaloo and Oduro, 2013). Species richness is also linked to increased biomass production in a wide range of ecosystems (Duffy et al., 2017).
Data collected	Number of different non-cocoa tree species of at least 10 cm dbh found within the plots from visual observation, confidently categorized as different from each other, without retrieving individual species name. Only additional new species not recorded on previous plots of a same field are counted. Oil palm trees and fruit trees are included. This option was taken to ensure the applicability of the method at large scale, with minimum resources and without the need of expert knowledge to identify each species.
Analysis	Evans estimator (Evans et al., 1955), cited by Melo et al., 2003) $S = s \log(N+1) / \log(n+1)$ with S = estimated species richness expected to occur in N number of samples; s = number of species observed in n unit samples. N was calculated as the number of samples of the respective unit size (n, variable per method) required to cover 1 ha.

sampling plot corresponds to a strip of 2 m (measured from the borderline to the inner side of the farm) along the full length of the border. The area surveyed was proportional to the farm size (Fig. 3, RapidBAM 1).

Method 2 –Transect from GPS waypoints into the cocoa farm

This method used the GPS waypoints, taken at the border of the farm, as the starting point to create transects inside the field. Transects were 20 m long and 2 m wide (1 m on each side of the transect). The number of transects varied with farm size and shape, but at least 20 transects per cocoa field were made (min 800 m^2; Fig. 3, RapidBAM 2).

Method 3 – Sampling plot from border into the cocoa farm at different directions

This method established 4 sampling plots of 200 m^2 each (20 m × 10 m). The plots were created starting from the field edges inward and located at least 100 m apart from each other, at different directions. The area surveyed (800 m^2) was the same for every farm (Fig. 3, RapidBAM 3).

2.3.3. *Testing and selection of a RapidBAM*

The selection of the most suitable RapidBAM was done through a stepwise process, with the field work being divided in three phases: i) Calibration; ii) Testing; and iii) Evaluation (Fig. 1). Each phase was implemented in specific regions and districts in Ghana (Fig. 3) and included the application of different tools for data validation and method testing. Along the different steps, adjustments were made to the sampling and data collection procedures, following data analysis and stakeholder consultation. The field team comprised TMS technicians, researchers and collaborators familiar with the specific cocoa fields, who contacted the farmers and implemented the methodologies in the selected fields. To test the suitability of the approach applied for collecting number of species, without identifying the individual species name, an expert on local tree species was also present. The field sampling was applied by TMS surveyors trained for that purpose.

(i) The **calibration phase** had the purpose to verify the accuracy and consistency of the three methods, comparing the data captured by the three different sampling procedures with in-depth full assessments made beforehand on the same fields (here called reference data, Asare and Asare, 2008; Asare and Ræbild, 2016). The three RapidBAMs were applied in the same 40 cocoa fields, 20 in Ashanti Region and 20 in the Western Region (Fig. 1).

(ii) In the **testing phase**, the protocols of the methods were adjusted, following stakeholder consultations and the calibration results. The three refined methods were then applied to a new set of cocoa fields randomly selected within the areas covered by TMS. The aim was to assess the representativeness of the data captured by each method and the time feasibility of each one. The assessment of data accuracy was carried out in teams of 2 surveyors on 135 fields, using a mixed sampling model; i.e., applying 2 rotating methods per fields (2 out of the 3 methods) and ensuring a minimum number of cocoa fields re-sampled with multiple methods. For each surveyor team, the methods applied were rotated for every 5 fields to minimize bias.

The time feasibility of the RapidBAM was tested by 3 individual surveyors; each RapidBAM was repeated on 15 cocoa fields, to obtain a minimum sample regarding the time needed to complete each method. Each surveyor repeated each method on 5 different fields.

(iii) The **evaluation phase** started with the selection of a single method, based on the best performance obtained in previous steps through consultation with stakeholders. Subsequently, an auditing process of the selected method was implemented, to verify its reproducibility and the quality of the data obtained. The selected RapidBAM was applied twice on 400 fields, with a different surveyor repeating the same procedures on each cocoa field. Therefore, two samples were obtained for further evaluation: the initial sample, when the selected method was applied for a first time; and the audited sample, when the selected method was applied a second time in the same cocoa fields by a different surveyor.

In all three stages, the collaboration of the farmers was crucial. They participated voluntarily in the field surveys and helped surveyors map their cocoa fields' borders, establish the sample plots and also provided information on tree abundance on their cocoa fields (not included in the RapidBAM).

2.3.3.1. Data analysis. In each phase of field work, several statistical tests were applied to assess the accuracy and precision of the data. In the calibration phase, the reference data (Asare and Asare, 2008; Asare and Ræbild, 2016) were used as a baseline for comparing the performance of each RapidBAM. The reference data collected the number and size of mature trees, which were above a cocoa canopy of at least 8-years old.

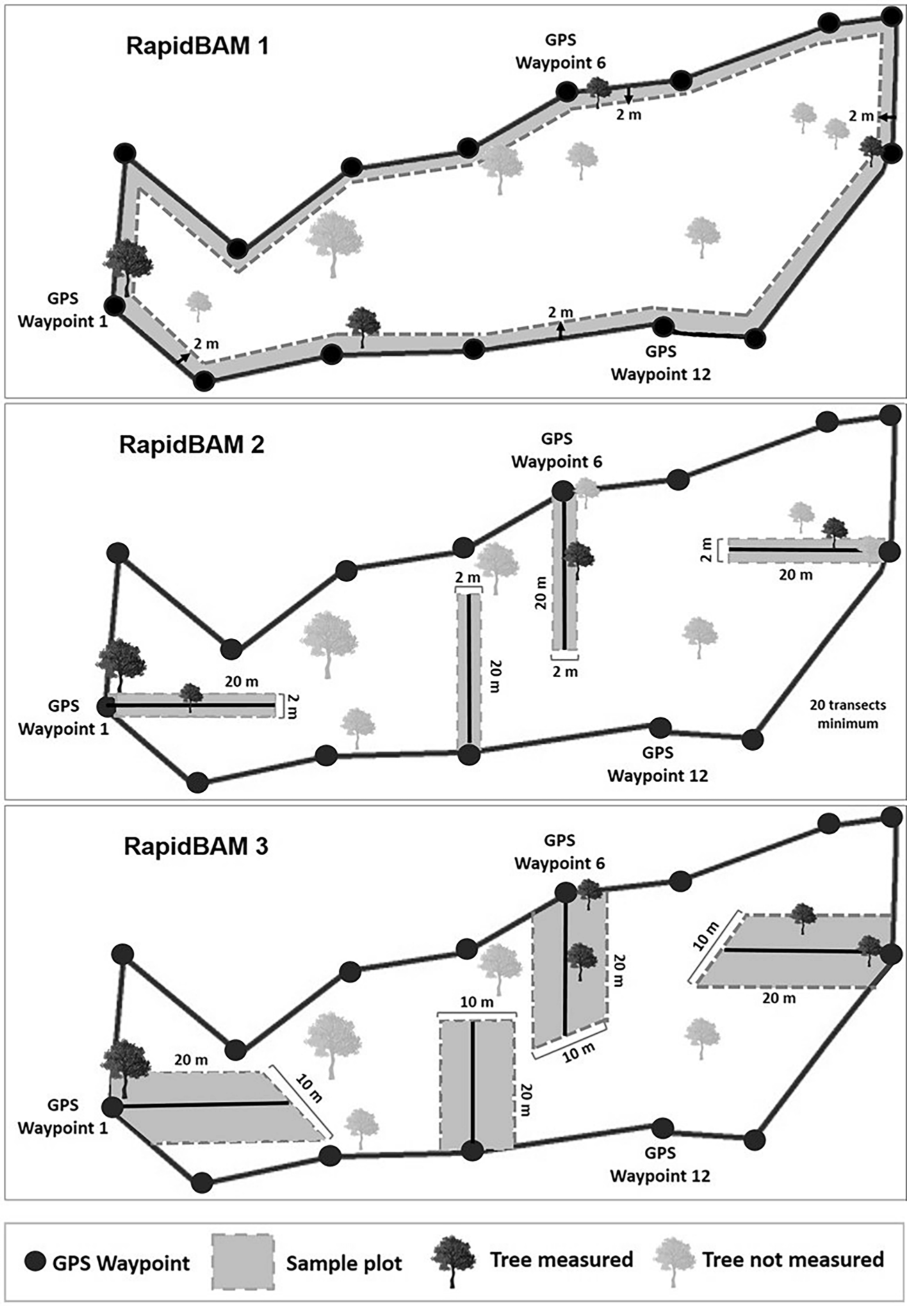

Fig. 3. Schematic representation of the sampling design for RapidBAM 1 (top), RapidBAM 2 (middle) and RapidBAM 3 (bottom). Not to scale.

However, the reference data did not include all the fruit trees that were initially included in the RapidBAMs, which could influence the trees and species counts. As such, only the number of trees above 30 cm dbh collected by the RapidBAM was compared to the reference data (as most fruit trees have smaller dbh). The Welch's *t*-test (Welch, 1938) was applied to compare the means and variance between each RapidBAM and the reference data, as well as among the three methods.

In the testing phase, besides each RapidBAM, we obtained three groups of paired methods. To compare >2 groups at the same time, the one-way ANOVA (analysis of variance) was applied, to verify possible differences between and within the groups (between the methods in the groups).

In the evaluation phase, we obtained two samples with the selected method, which were collected in the same cocoa fields by different surveyors; as such, these two samples are not completely independent. For this reason, the Wilcoxon test (Wilcoxon, 1945) was used instead, to assess the precision of the method selected by comparing the ranks between the two dependent samples (initial and audited).

3. Results

3.1. Calibration phase

There were significant differences (p-value < 0.05) between the RapidBAMs, depending on the primary indicator considered. RapidBAM1 shows the highest mean values for density of trees and species richness, but also higher variability (reflected in standard deviation values) amongst sampled fields in relation to other methods (except when compared to RapidBAM 2 for trees/ha) (Table 3). RapidBAM1 and RapidBAM2 showed no significant difference in number of trees, whereas they were both significantly different from RapidBAM3, which registered fewer trees (Table 4). Regarding species per ha, RapidBAM2

Table 3
Descriptive statistics of trees/ha and species/ha for each RapidBAM and the reference data.

Trees (>30 dbh) per ha	mean	sd	median	min	max
RapidBAM 1	41	25	37	0	92
RapidBAM 2	38	30	37	0	138
RapidBAM 3	21	17	13	0	75
Reference Data	18	15	14	4	70
Species per ha	**mean**	**sd**	**median**	**min**	**max**
RapidBAM 1	25	10	25	8	56
RapidBAM 2	10	5	11	2	21
RapidBAM 3	10	5	10	2	20
Reference Data	12	10	10	2	54

Ref – Reference data; RapidBAMs identified with the number (1, 2 and 3). p-value – significance. N = 40 fields.

Table 4
Results of the *t*-test for number of trees/ha (above 30 cm dbh) between each RapidBAM and the reference data.

Trees (>30 dbh) per ha	T-value	df	p-value
RapidBAM [1 ~ 2]	0.498	75.82	0.620
RapidBAM [1 ~ 3]	4.282	67.96	0.000*
RapidBAM [2 ~ 3]	3.213	61.39	0.002*
Ref ~ RapidBAM1	−4.925	64.57	0.000*
Ref ~ RapidBAM2	−3.744	58.32	0.000*
Ref ~ RapidBAM3	−0.692	77.42	0.491

Ref – Reference data; RapidBAMs identified with the number (1, 2 and 3). p-value – significance; if the p-value is less than 0.05, the difference between methods is significant at 95% level and is marked with *. df – degrees of freedom. N = 40 fields.

and RapidBAM3 were not significantly different from each other, unlike what was found for RapidBAM 1 with 2.5 times as many species (but again with higher variability) (Table 5).

In relation to the reference data, RapidBAM3 was the only method that showed no significant differences for both parameters (Tables 4 and 5). RapidBAM2 showed differences with regards to trees per ha, whereas RapidBAM1 showed significantly different results for both trees and species and the largest difference in relation to the reference data, indicating potential overestimation of the sampling procedure. The recording of additional trees with the transect at the border may be the result of several factors. On the one hand, the exact boundary of the field identified by the farmer may slightly change over time, as borders are not physically and/or permanently marked. On the other hand, surveyors may have also included trees that were not completely within the transect plot.

3.1.1. *Adjustments for the Testing phase*

Based on these results, the methods were adjusted for further application in the testing phase. Overestimation by the RapidBAMs, especially RapidBAM1, was identified as an issue, so an additional criterion in the sampling procedure was included, to count only those trees with at least half their trunk falling within the transect area. Secondly, additional training on species' identification was provided, to assist surveyors in identifying a tree as a different species within the multiple sample plots on the cocoa fields.

Table 5
Results of the *t*-test for number of species/ha (above 30 cm dbh) between each RapidBAM and the reference data.

Species per ha	T-value	df	p-value
RapidBAM [1 ~ 2]	8.478	53.72	0.000*
RapidBAM [1 ~ 3]	8.133	57.36	0.000*
RapidBAM [2 ~ 3]	−0.268	76.87	0.789
Ref ~ RapidBAM1	−5.671	78.00	0.000*
Ref ~ RapidBAM2	1.167	53.85	0.248
Ref ~ RapidBAM3	0.981	57.51	0.331

Ref – Reference data; RapidBAMs identified with the number (1, 2 and 3). p-value – significance; if the p-value is less than 0.05, the difference between methods is significant at 95% level and is marked with *. df – degrees of freedom. N = 40 fields.

3.2. *Testing phase*

The rotating pairs of methods defined for the testing phase resulted in the following number of farms: Group 1 - RapidBAM [1 + 2], n = 43; Group 2 - RapidBAM [1 + 3], n = 43; Group 3 - RapidBAM [2 + 3], n = 35. The final sample size varied slightly per group of methods, due to the exclusion of some incomplete observations. The mean area surveyed is similar between all methods, ca. 800 m^2, with slight variations for RapidBAM1, as it entirely depended on the farms border. In contrast to the previous phase, RapidBAM1 recorded lower mean values for number of trees and species per ha, when compared to the other methods (Table 6). This is likely related to the additional criterion defined, specifically requiring that the trees/species would be counted only when at least half their trunk would fall within the sample plot, otherwise they were disregarded. On the other hand, RapidBAM2 recorded the highest mean values in number of trees, indicating a potential overestimation, which could be due to the design of the sampling procedure and the size and shape of the farms surveyed (Table 6). The average size of the sampled fields surveyed at this stage was low (0.76 ha across the methods in the different groups) and this may have caused an overlap between the 20 m long × 2 m wide transects done on the fields, implying the count of the same tree more than once. Transects were done while mapping the border of the farm, when a new waypoint was recorded in the GPS and could not be previously determined. This overlap of plots was less probable to occur for RapidBAM3, and not possible to happen with RapidBAM1.

The ANOVA results showed significant differences between the methods, regarding the mean values of both parameters (Table 7, Between Methods), whereas no significant differences were found between the groups of paired methods (Table 7, Between Groups). These results indicate that any difference found is derived from the sampling procedure of each RapidBAM, rather than the grouping of methods.

3.2.1. *Time assessment*

In relation to the time needed to implement the sampling procedure, on average RapidBAM1 took 15 min, RapidBAM2 took 45 min, and RapidBAM3 took 37 min to complete. RapidBAM2 was more time-consuming than the other methods and did not comply with the requirement of ca. 30 min. RapidBAM1 took less time in the farms surveyed, however as it depends entirely on the farm border and size, the time required to apply the method could vary greatly in different contexts.

3.2.2. *Selection of a RapidBAM*

A comparison was made of the advantages and limitations between the three methods, regarding data accuracy, time and simplicity. These were discussed in stakeholder consultations, resulting in a consensus that RapidBAM 3 should be selected for further evaluation in the following phase. This particular method simplified field work implementation and required less time to complete, since it relied on a lower number of sample plots, which also facilitated the identification of new

Table 6
Mean values of trees per ha and species per ha for each method, among the 3 groups.

Method (among the 3 groups)	Mean trees per ha	Mean species per ha
RapidBAM 1	52	5
RapidBAM 2	83	10
RapidBAM 3	67	10

Table 7
Results of ANOVA for number of trees and species per ha, for differences between groups and within groups (between the methods in the groups).

Trees/ha	Df	Sum sq	Mean sq	F-value	Pr(>F)
Between Groups	2	3569	1784	0.68	0.510
Between Methods	2	63,239	31,620	11.96	0.000*
Species/ha	**Df**	**Sum sq**	**Mean sq**	**F-value**	**Pr(>F)**
Between Groups	2	110	55.1	1.42	0.244
Between Methods	2	1626	813.1	20.95	0.000*

Df – degrees of freedom. Pr(>F) – significance; if the p-value is less than 0.05, the difference between methods is significant at 95% level marked with *.

species found on sample plots. Moreover, a higher accuracy was obtained when compared to reference data from the in-depth assessments, since this was the only method without significant differences in both primary indicators (number of trees and number of species). To ensure applicability of this method at large scale, some additional adjustments were made to improve the sampling procedure. Key changes included: i) modifying the form structure to facilitate its compilation; ii) counting palm trees and plantain separately from the other non-cocoa trees and iii) selecting specific waypoints to set the plots, to ensure randomness of the sampling and a more regular distribution of sampling plots within the farm. As such, the sampling protocol was revised to include setting the plots only after a change of cardinal direction and at a minimum of 100 m distance from each other (Supplementary materials, Figures S1 and S2). In addition, the species list to provide to farmers should be updated with local tree species name according to the region where the method is implemented.

3.3. Evaluation phase

3.3.1. Initial and audited samples

From each of the fields surveyed (n = 403), two samples were obtained during this phase. The initial sample represents the first time that RapidBAM3 was applied in a field by a surveyor, and the audited sample represents the second time RapidBAM3 was applied in the same farm by a different surveyor. Results showed no significant differences for number of trees (W = 25085, p-value = 0.8653), whereas number of species showed significant differences between the initial and the audited samples (W = 32967.5, p-value < 0.0001). These results provide valuable indications on the replicability of the method; the discrepancy between the two samples obtained for number of species can be a challenge, considering that surveyors are required to distinguish species without having expert knowledge.

3.4. Data provided by farmers

In several phases of the field work, farmers voluntarily compiled a form indicating the number of trees for each tree species that, according to them, existed in their cocoa fields.

During the calibration phase, we found that the number of species per ha that farmers provided was not significantly different than the reference data (t = -1.38, df = 69.16, p-value = 0.172). However, there was a significant difference regarding number of trees per ha (t = -4.4587, df = 53.35, p-value = 0.0428), with the reference data showing overall lower mean values.

In relation to the RapidBAM tested, the number of species given by the farmers was generally higher than the estimations obtained with the three methods, but this difference is not significant for RapidBAM3 (*t*-test = -1.6364, p-value = 0.1047), that relies on a lower number of sample plots and, as such, it facilitates the identification of tree species. by non-expert surveyors. Conversely, the number of trees given by the farmers were generally lower than the values obtained from the sampling methods.

In the evaluation phase, an updated inventory procedure was implemented, which included further assistance from the surveyor in compiling the form given to local farmers, to reduce inaccuracies eventually caused by illiteracy. It was found that the differences in species per ha, between the initial and audited samples, were not significant (W = 1244, p-value = 0.1011), and at least 50% of the cocoa fields showed no difference in species number. On the contrary, the number of trees per ha showed significant differences (W = 4780, p-value = 0.0127), with higher values for the initial sample in relation to the audited one.

4. Discussion

The development of rapid biodiversity assessments for agroforests can have a relevant contribution to global efforts of biodiversity monitoring and conservation (Asigbaase et al., 2019). The use of such methods for crops and their potential applicability at large scales, provide the opportunity to address both sustainable production and biodiversity conservation goals, by helping farmers adhere to biodiversity-friendly practices to increase productivity, and by consistently obtaining data to monitor biodiversity conditions over time.

The stepwise framework implemented allowed the selection of a rapid biodiversity assessment method that complied best with the proposed objectives of data accuracy, affordability, simplicity of the sampling procedure and possible integration in a GIS mapping and traceability platform. The implementation of different field work phases allowed for progressive improvements in the sampling procedures, based on field experience, surveyors and stakeholder feedback, and on the results obtained in preceding phases. The methodology here presented is applied at cocoa field level and allows obtaining data for each field, while simultaneously providing information on spatial patterns for specific areas, due to its integration in a wider system for traceability and mapping of cocoa fields.

The implementation of such sampling protocol at large-scale, based on field surveys, depends on the collaboration of farmers. Their participation in the whole process of the method's implementation can also contribute to ensuring the applicability of the method and its sustainability. The results obtained in this research suggest that farmers' knowledge could be utilized as a reliable means for obtaining qualitative species level information that could complement the data collected by the rapidBAM. However, a deeper understanding of their perception regarding number of trees on-farm and the clarification of tree definition is required. Our results evidence the need to further explore if the definition of a tree applied in this research (>10 cm dbh and several uses, such as timber and fruit trees) could be a reason for the difference in reported numbers by the farmers. Previous research has suggested that differences in tree definition also existed among farmers, depending if they were migrants or not (Ruf, 2011).

The integration of farmers' knowledge on the data collection procedure is consistent with the citizen-science approaches that have been implemented for biodiversity conservation, allowing to obtain high volumes of data that can be introduced in scientific protocols and complement other data collection procedures (Chandler et al., 2017; McKinley et al., 2017; Pocock et al., 2017). As shown in prior studies, the farmer is a valuable source of information (Hellier et al., 1999; Orozco et al., 2008; Tesfahunegn et al., 2016) and can assist in the application of a quick and accurate procedure for data collection on their farms. The direct participation of farmers in scientific activities can foster knowledge transfer and increase their awareness for the issues being studied. As potential beneficiaries of the results of such research (for example, through training on biodiversity-friendly practices), the access of farmers to up-to-date and reliable information can help them improve their farming practices, achieve certification standards, mitigate climate change impacts and increase cocoa yields, therefore benefiting their household as well (De Beenhouwer et al., 2013; Jagoret et al., 2014; Tschora and Cherubini, 2020).

As found by prior research, and despite the usefulness of citizen-science approaches, some caution is needed due to bias and noise introduction in data collection (Callaghan et al., 2019). Our results have also shown that there were discrepancies in the recording of number of species, since surveyors were required to distinguish species without having expert knowledge. Nevertheless, based on the experience obtained with the stepwise approach, this issue can be reasonably overcome by providing additional training to local surveyors. During the several phases of field work, we found that a precise definition of what type of trees to include, simplified data collection forms and more training on species identification, were key conditions for the success of the initiative at broad scale. Also, field surveys such as the RapidBAM proposed, can be integrated with other data collection approaches to integrate traceability and monitoring frameworks, such as remote sensing, particularly very-high resolution images. Even though these technologies are still rather costly and require additional resources and expertise (Stephenson, 2020), the combination of multiple data sources and collection techniques for biodiversity monitoring at a large scale should be further investigated.

Other agroforest characteristics, such as shade cover, vegetation structure or above-ground carbon stocks, can be obtained from the data on number of species, number of trees and their size ranges (from dbh), as collected by the RapidBAM described. These rapid assessment methods can, therefore, provide valuable information also on environmental conditions and ecosystem services (Daghela Bisseleua et al., 2013; Kuyah et al., 2019; Saj et al., 2013). An alternative research step would be the application of the selected RapidBAM on a large set of cocoa fields and the analysis of the patterns therein obtained. For effective implementation and scalability of this methodology in different commodity-based agroforestry systems and country contexts, it is recommended that several adaptation steps should be taken, specifically: update the most common on-farm tree species and their local names for farmer data collection forms and surveyor species identification training; address potential variations to the minimum distance between sampling plots according to the average farms shapes and sizes and, where possible, calibrate the method with in-depth assessments, as it was done in the first phase of this research (during the calibration and testing phases).

5. Conclusions

This paper presented the procedure developed to select a rapid biodiversity assessment method to be applied at large-scale in cocoa fields, and potentially in other agroforestry systems. The three methods initially proposed were designed to collect a set of pre-defined indicators regarding non-cocoa trees on farms and were tested in several phases. The use of a progressive decision-making process and the participation of different institutions, experts and local people with diversified experience, were important factors that enabled developing a RapidBAM that is relevant and useful to multiple stakeholders, including private sector and certification bodies.

The selection of a RapidBAM reflected an agreement between the need of a systematic data collection procedure and the limited availability of resources to apply it at large-scale. Despite the lower requirements of strong technical knowledge and skills when compared to in-depth biodiversity assessment methods, the final RapidBAM was able to provide reasonable estimations of biodiversity parameters and generate results that were not significantly different from those obtained from extensive field work.

The major implications of this research are reflected in the stepwise development of a scalable rapid biodiversity assessment method that is easy to apply with local knowledge, with minimum training required and time-efficient. Furthermore, the methodology can be integrated into existing geographic information systems as an additional module or it can be used as a stand-alone biodiversity assessment tool. Future work should focus on further validating this procedure with large scale assessments in cocoa agroforests, on its integration with other data collection techniques and on its potential transferability to other contexts.

CRediT authorship contribution statement

Jessica E. Raneri: Conceptualization, Formal analysis, Methodology, Project administration, Visualization, Writing - original draft. **Sandra Oliveira:** Formal analysis, Data curation, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft. **Nicole R. Demers:** Investigation, Project administration, Visualization, Writing - review & editing. **Richard Asare:** Data curation, Methodology, Writing - review & editing. **Seth Nuamah:** Data curation, Investigation, Validation, Writing - review & editing. **Mustapha Dalaa:** Data curation, Investigation, Validation, Writing - review & editing. **Stephan Weise:** Conceptualization, Methodology, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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